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Analysis of the drought resilience of Andosols on southern Ecuadorian Andean páramos

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Abstract

The neotropical Andean grasslands above 3500 m a.s.l. known as "páramo" offer remarkable ecological services for the Andean region. Most important is the water supply – of excellent quality – to many cities and villages established in the lowlands of the inter-Andean valleys and to the coast. However, the páramo ecosystem is under constant and increased threat by human activities and climate change. In this paper we study the resilience of its soils for drought periods during the period 2007–2013. In addition, field measurements and hydrological conceptual modelling at the catchment-scale are comparing two contrasting catchments in the southern Ecuadorian Andes. Both were intensively monitored during two and a half years (2010–2012) in order to analyse the temporal variability of the soil moisture storage. A typical catchment on the páramo at 3500 m a.s.l. was compared to a lower grassland one at 2600 m a.s.l. The main aim was to estimate the resilience capacity of the soils during a drought period and the recovery during a subsequent wet period. Local soil water content measurements in the top soil (first 30 cm) through TDR were used as a proxy for the catchment's average soil moisture storage. The local measurements were compared to the average soil water storage as estimated by the probabilistic soil moisture (PDM) model. This conceptual hydrological model with 5 parameters was calibrated and validated for both catchments. The study reveals the extraordinary resilience capacity of this type of shallow organic soils during the droughts in 2009 and 2010. During these droughts, the soil water content dropped from a normal value of about 0.80 to $\sim 0.60\,\mathrm{cm^3\,cm^{-3}}$, while the recovery time was only two to three months.

1 Introduction

In the northern Andean landscape, between ca. 3500 and 4500 m a.s.l., an "alpine" neotropical grassland ecosystem – locally known as "páramo" – covers the mountains. Their major ecological characteristics has been documented by several authors (e.g.

Buytaert et al., 2006a; Hofstede et al., 2003; Luteyn, 1999). The páramo is an endemic ecosystem with high biodiversity. Its soils contain an important carbon storage and provide a constant source for drinking water for many cities, villages, irrigation systems and hydro-power plants. During the last years, a high vulnerability of these systems to changes induced by human activities and climate change in mountainous regions has been recognized. Most of the research in páramos has been focused on its hydrological capacity as well as the soil characteristics under unaltered and altered conditions (Buytaert et al., 2007a; Farley et al., 2004; Hofstede et al., 2002; Podwojewski et al., 2002). These researches recognize the key role of the páramos in the water supply in the Andean region. The hydrological capacity is mainly related to the characteristics of its soils. Shallow organic soils – classified according to the WRB as Andosols and Histosols – are the two main groups of soils that can be found in this Andean region. These soils are characterized by high levels of organic matter. They have an immense water storage capacity which reduces flood hazards for the downstream areas, while sustaining the low flows all year round for domestic, industrial and environmental uses.

Nevertheless, the páramo area is under threat by the advancement of the agricultural frontier. Additionally, flawed agricultural practices cause soil degradation and erosion. Former studies on soil water erosion reveals significant soil loss in the highlands of the Ecuadorian Andean as result of land use changes (Vanacker et al., 2007) but also tillage erosion is responsible for this soil loss and for the degradation of the water holding capacity (Buytaert et al., 2005; Dercon et al., 2007).

Land cover changes have also occurred in páramo. In the seventies, some areas of páramo were considered appropriate for afforestation with exotic species such as *Pinus radiate* and *Pinus patula*. The main goal was to obtain an economical benefit from this commercial timber. The negative impact of this afforestation and the consequences on the water yield of the páramo have been described by Buytaert et al. (2007b). Also, the productivity was rather disappointing, due to the altitude.

The potential impact of the climate change over alpine ecosystems has also been reported by Buytaert et al. (2011) and Viviroli et al. (2011). Mora et al. (2014) predict an increase in the mean annual precipitation in the region that is of interest to our study. On the other hand, the carbon storage and the water yield could be reduced by the higher temperatures and the higher climate variability. However, the uncertainties on the potential impact of the climate change remain high (Buytaert and De Bièvre, 2012; Buytaert et al., 2010).

Another important factor for the region are the El Niño Southern Oscillation events. The Amazon river basin, with its headwaters in the Andes, has indeed faced severe droughts in 2005 and 2010 (Lewis et al., 2011; Phillips et al., 2009). These dry periods have been attributed to the severe El Niño Southern Oscillation events and northwest displacement of the intertropical convergence zone (ITCZ) (Marengo et al., 2008, 2011).

The El Niño Southern Oscillation events not only have an impact on the ecohydrology of the forest area of the Amazon River basin but also in its headwater or páramos. Indeed, the droughts in the páramo have been observed during the months with less rainfall (from September to December), which coincide with the displacement of the ITCZ and by the Pacific and Atlantic anomalies (Buytaert et al., 2006b; Vuille et al., 2000). Thus, the climate variability in the mountains is exacerbated by these climate global events.

Since 2004 droughts in the páramo took place in 2005, 2009, 2010, 2011 and 2012, of which the first three years have been classified as "el Niño" years. The drought periods in the páramo had a negative impact on the water supply and on the economy of the whole region that depends on water supply from the Andes. For instance, the water levels in the reservoirs of the main hydropower projects reached their lowest values as a consequence of the drought between December 2009 and February 2010. This caused several, intermittent, power cuts in many regions of Ecuador.

The hydrological capacity of the páramo resides on its soils. Therefore the present study investigates the response of páramo' soils to drought and compares with other soils on grasslands at lower altitude in the same region. The drought analysed is a soil moisture drought as defined by Van Loon (2015). The resilience or resistance to drought is defined here as the time needed to recover to its pre-drought state of water content once that rainfall has started in a continuous way to exceed the vegetation water demand. The pre-drought state of soil water content is estimated from longer term periods whereby rainfall exceeds the vegetation requirements. The observation period includes the droughts of 2009, 2010, 2011 and 2012 together with intermediate wet periods. The analysis is done with special focus on the 2010 drought.

The hydrological drought is compared and related to this soil water drought. For this purpose, the water balance components of two experimental catchments – one with and one without páramo – were investigated by means of experimental measurements and by means of a hydrological model. The experimental work included the measurement of rainfall, flow and soil moisture. For the modelling, a parsimonious conceptual hydrological model – using the Probability Distributed Moisture simulator (PDM) was calibrated and validated for each experimental catchment. The PDM model allows to analyse the spatial variability of the soil water content as well as the maximum storage capacity at the catchment scale. Therefore, the representativeness of the point measurements of soil water content can be assessed by means of this model.

Our main hypothesis is that experimental monitoring combined with mathematical models enables the quantification of the sensitivity – or resilience – to drought of the land cover and soil systems in the Andes above 2600 m a.s.l.

2 Materials

2.1 The study area

The catchments under study are located in the southwest highlands of the Paute river basin, which drains to the Amazon River (Fig. 1). These highlands form part of the Western Cordillera in the Ecuadorian Andes with a maximum altitude of 4420 m a.s.l. The study area comprises a mountain range from 2647 until 3882 m a.s.l. Two catchments have been selected from this region: Calluancay and Cumbe.

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The Calluancay catchment has an area of 4.39 km^2 with an altitude range between 3589 and 3882 m a.s.l. and a homogeneous páramo cover. The páramo vegetation consists mainly of tussock or bunch grasses and very few trees of the genus *Polylepis*. These trees are observed in patches sheltered from the strong winds by rock cliffs or along to some river banks in the valleys. Furthermore, in saturated areas or wetlands huge cushion plants are surrounded by mosses. This vegetation is adapted to extreme weather conditions such as low temperatures at night, intense ultra-violet radiation, the drying effect of strong winds and frequent fires (Luteyn, 1999). The land use of Calluancay is characterized as extensive livestock grazing.

The second catchment, Cumbe, drains an area of 44 km^2. The highest altitude reaches 3467 m a.s.l., whereas the outlet is at an altitude of 2647 m. This altitude range of almost 1000 m gives a typical Andean mountain landscape with steep slopes and narrow valleys where the human intervention is also evident. This catchment is below the 3500 m and therefore contains a negligible area of páramo. The most prominent land cover is grassland (38.1 %) along with arable land and rural residential areas (26.9 %). A sharp division between the residential areas and the small scale fields is absent. Mountain forest remnants are scattered and cover 23 % of the area, often on the steeper slopes. At the highest altitude (> 3300 m) sub-páramo is predominant; it occupies only 7.6 % of the catchment. In the Cumbe, about 4.4 % of the area is degraded by landslides and erosion.

A small village, Cumbe, is located in the valley and on the lower altitudes of the catchment. This village has ca. 5550 inhabitants. The water diversions from streams in Cumbe are ca. 12 [$L s^{-1}$] in total, mainly for drinking water. The village has no waste water treatment and used water is discharged via septic tanks. Additionally, during dry periods two main open water channels for surface irrigation are enabled. The water diversion and its rudimentary hydraulic structures have been built upstream of the outlet of the catchment. These irrigation systems deliver water to the valley area occupied by grasslands and small fields with crops.

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Several types of soils can be identified in Cumbe and Calluancay, which are mainly conditioned by the topography. Dercon et al. (1998, 2007) have described the more common toposequences in the southern Ecuadorian Andes according to the WRB classification (FAO/ISRIC/ISSS, 1998). Cumbe has a toposequence of soils from Vertic Cambisols, located in the alluvial area, surrounded by Dystric Cambisols at the hillslopes in the lower and middle part of the catchment. Eutric Cambisols or Humic Umbrisols extend underneath the forest patches between 3000 and 3300 m a.s.l. The highest part of the catchment – from 3330 until 3467 m a.s.l. – is covered by Humic Umbrisols or Andosols.

In contrast, Calluancay hosts only two groups of organic soils under páramo: Andosols (in the higher and steeper parts) and Histosols (in the lower and gentler parts of the catchment). The soils were formed as the geology of Calluancay is characterized by igneous rocks such as andesitic lava and pyroclastic igneous rock (mainly the Quimsacocha and Tarqui formations, dating from the Miocene and Pleistocene respectively), forming an impermeable bedrock underneath the catchment. In the Cumbe catchment, the highlands and some areas of the middle part (about 55 % of the area) are characterized by pyroclastic igneous rocks (mainly the Tarqui formation). The valley area (37 % of the basin) is covered by sedimentary rocks like mudstones and sandstones (mainly the Yunguilla formation, dating from the upper Cretaceous). Only 8 % of the Cumbe catchment comprises alluvial and colluvial deposits, which date from the Holocene (Hungerbühler et al., 2002).

2.2 The monitoring data

An intensive monitoring with a high time resolution was carried out in the study area during 28 months.

The gauging station at the outlet of Cumbe consists of a concrete trapezoidal supercritical-flow flume (Kilpatrick and Schneider, 1983) and a water level sensor (WL16 – Global Water). Logging occurs at a 15 min time interval. Regular field measurements of the discharge were carried out to cross-check the rating curve.

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The measurements at Calluancay are part of a larger hydrological monitoring network maintained by PROMAS. Water levels are logged every 15 min at two gauging stations, which consist of a concrete V-shaped weir with sharp metal edges and a water level sensor (WL16- Global Water). The first station is installed at the outlet of the catchment. The second gauging station monitors an irrigation canal to which water is diverted from the main river. The gauging station was installed where the canal passes the water divide of the catchment. So, the total discharge can be evaluated.

For the Calluancay, rainfall is measured by a tipping bucket rain gauge (RG3M-Onset HOBO Data Loggers) located inside the catchment and with a resolution of 0.2 mm.

Three similar rain gauges were installed in the larger Cumbe catchment and located at the high, middle and lower part of the catchment. The areal rainfall for Cumbe was calculated with the inverse distance weighing (IDW) method, using the R implementation of GSTAT (Pebesma, 2004).

In each experimental catchment an automatic weather station measured the meteorological variables such as air temperature, relative humidity, solar radiation and wind speed at a 15 min time interval. These stations were used to estimate the potential reference evapotranspiration according to the FAO–Penman–Monteith equation.

2.3 The physical characteristics of the soil

In both catchments, the soil moisture content of the top soil layer was measured by means of time domain reflectometry (TDR) probes at representative sites in the vicinity of the weather stations. In both catchments, 6 TDR probes were installed in each plot. The TDRs were installed vertically from the soil surface with a length of 30 cm and logged at 15 min time intervals. In Calluancay, every fortnight soil water content was also measured by sampling from November 2007 until November 2008. In this catchment the TDR time series was from May 2009 until November 2013. In Cumbe, the TDR-time series extends from July 2010 until November 2012.

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For Cumbe and Calluancay, the TDR measurements were calibrated based on soil samples (R^2 = 0.79 and 0.80 respectively). In addition, the curves were regularly cross-validated by undisturbed soil samples during the monitoring period.

The soil water retention curves were determined based on undisturbed and disturbed soil samples collected near to the TDR probes. In the laboratory, pressure chambers in combination with a multi-step approach allowed to define pairs of values for moisture (θ) and matric potential (h). The soil water retention curve model proposed by van Genuchten (1980) was fitted on the data.

3 Methods

3.1 The water balance based on the experimental data

The soil water balance of the root zone in each catchment over a selected time interval is estimated by the following equation:

$$\frac{\mathrm{d}S_\mathrm{r}}{\mathrm{d}t} = P - E_\mathrm{a} - Q_\mathrm{o} - Q_\mathrm{l} + C_\mathrm{r} - D_\mathrm{p} \quad (1)$$

where $\mathrm{d}S_\mathrm{r}$ = the storage variation in the root zone during the time interval [mm], $\mathrm{d}t$ = the length of the time interval [days], P = the precipitation intensity during the time interval [mm day^{-1}], E_a = the actual evapotranspiration rate during the time interval [mm day^{-1}], Q_o = the overland flow during the time interval measured at the outlet of the catchment [mm day^{-1}], Q_l = the lateral flow during the time interval [mm day^{-1}], C_r = the capillary rise from a water table during the time interval [mm day^{-1}] and D_p = the deep percolation rate during the time interval [mm day^{-1}].

In the Cumbe catchment some water is diverted from the river for irrigation. As a result the flow at the outlet is reduced by the amount of irrigation. This irrigation is mainly concentrated in the valley and is rather informal by small farmer constructed

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offtakes without major hydraulic structures. In addition there are no irrigation associations present and therefore an estimation of this withdrawal is very difficult.

Based on geological data, in Calluancay the deep percolation and capillary rise are considered to be negligible since the soils overlay bedrock consisting of igneous rocks with limited permeability. In páramos, the saturation overland flow is the dominant flow processes of runoff generation (Buytaert and Beven, 2011). The stream discharge (Q) at the outlet of the catchment thus comprises mainly overland flow and lateral flow.

In Cumbe, a surface-based electrical resistivity tomography test (Koch et al., 2009; Romano, 2014; Schneider et al., 2011) revealed no significant shallow groundwater for the alluvial area. In addition, the flat alluvial area near the catchment outlet is very small (2.7 % of the catchment area). Therefore, the terms D_p and C_r are also regarded to be negligible.

Based on the soil texture in Cumbe (clay) it is inferred that the infiltration overland flow is the dominant flow process of runoff generation. As a result, the stream discharge in Cumbe will be constituted, as in Calluancay, by two kinds of flows: overland and lateral flow.

Considering that the overland flow (Q_o) and the lateral flow constitute the observed river flow, Q, the water balance in our two catchments can thus be written as:

$$\frac{dS_c}{dt} = P - E_a - Q \quad (1a)$$

where dS_c = the average storage variation in the soil of the catchment during the time interval [mm] and Q = the total runoff leaving the catchment during the time interval [mm day^{-1}].

If we consider that P and Q are measured and we assume that the change of storage can be estimated based on the TDR measurements in our sampling points (as we will show in the results section), the actual evapotranspiration is the only unknown in this equation.

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During wet periods the water content in the root zone is constant at field capacity. The continuity equation may then be reduced to:

$$E_a = P - Q \tag{1b}$$

3.1.1 The potential evapotranspiration

The FAO–Penman–Monteith approach (Allen et al., 1998) is used to estimate the potential evapotranspiration of a reference crop (grass):

$$E_p = \frac{0.408\Delta(R_n - G_h) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where E_p = the potential reference evapotranspiration [mm day^{-1}], R_n = the net radiation at the crop surface [MJ m^{-2} day^{-1}], G_h = the soil heat flux density [MJ m^{-2} day^{-1}], T = the mean daily air temperature at 2 m height [°C], u_2 = the wind speed at 2 m height [m s^{-1}], e_s = the saturation vapour pressure [kPa], e_a = the actual vapour pressure [kPa], $e_s - e_a$ = the saturation vapour pressure deficit [kPa], Δ = the slope of the vapour pressure curve [kPa °C^{-1}] and γ = the psychrometric constant [kPa °C^{-1}].

The suitability of the FAO–Penman–Monteith approach for high altitudinal areas has been evaluated by Garcia et al. (2004). They found that the FAO-approach gives the smallest bias (−0.2 mm day^{-1}) as compared to lysimetric measurements.

The measurements of the solar radiation in our experimental catchments were not consistent and appeared to be unreliable. Therefore, the FAO–Penman–Monteith estimation for E_p was used with the solar radiation estimated by means of the Hargreaves–Samani equation (Hargreaves and Samani, 1985) using the daily maximum and minimum air temperature:

$$R_s = R_a\, c\, (T_{max} - T_{min})^{0.5} \tag{3}$$

where R_s = the solar radiation [MJ m^{-2} day^{-1}], R_a = the extra-terrestrial solar radiation [MJ m^{-2} day^{-1}], c = an empirical coefficient [–] and T_{max}, T_{min} = the daily maximum

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and minimum air temperature respectively [°C]. According to Hargreaves and Samani (1985) "c" has a value of 0.17 for inland areas.

3.1.2 The actual evapotranspiration

The FAO–Penman–Monteith approach is used to calculate the potential evapotranspiration of a reference crop (normally grass) under stress free conditions without water limitation (E_p). This reference crop evapotranspiration can be converted to the evapotranspiration of another vegetation type by means of a vegetation coefficient k_v. During dry periods, with water stress, the vegetation extracts less water as compared to the vegetation requirement. The relative reduction of the evapotranspiration due to this may be expressed by a water stress coefficient k_s.

The actual evapotranspiration, E_a, can thus be calculated as:

$$E_a = k_s \cdot k_v \cdot E_p \tag{4}$$

In general, k_v is time-dependent, as it is linked to the growth cycle of the vegetation and thus to the season. For the páramo, this seasonality may be neglected as the grasses are slow-growing and perennial. In our study we therefore calculate a constant k_v by considering wet periods (during which $k_s = 1$) and using Eq. (4), in combination with the equations 1b (for calculating E_a) and 2 (for calculating E_p). Hereby, the wet periods were identified based on the TDR measurements of the soil water content.

Below the critical water content, E_a becomes less than the vegetation requirement and the soil water stress coefficient may be calculated as (Seneviratne et al., 2010):

$$k_s = 1 - \frac{\theta_{crit} - \theta_{act}}{\theta_{crit} - \theta_{wp}} \tag{5}$$

where θ_{crit} is the critical soil water content, θ_{act} is the actual soil water content and θ_{wp} is the permanent wilting point of the soil.

With k_v derived during wet periods as described above, k_s can now be estimated as a function of the actual soil moisture content by considering the (daily) water balance during dry periods. Hereto, we combine the Eqs. (1a), (4), (2) and (5). If we consider that the permanent wilting point can be derived from the soil water retention curve, based on the soil and vegetation characteristics, the critical soil water content is the only parameter that needs to be determined.

3.2 The actual evapotranspiration estimated by hydrological modelling

The actual evapotranspiration estimation based on local soil water measurements is compared to the actual evapotranspiration at catchment-scale calculated by the PDM model (Moore and Clarke, 1981; Moore, 1985). This hydrological model will be used to assess the impact of the soil moisture on the evapotranspiration. The PDM is a lumped rainfall–runoff model and its structure consists of two modules. The first is a soil moisture accounting (SMA) module which is based on a distribution of soil moisture storages with different capacities used to account for heterogeneity in the catchment. The probability distribution used is the Pareto distribution. The second part of the model structure is a routing module which consist of two linear reservoirs in parallel in order to consider the fast and slow flow pathways respectively. As in our study we consider small basins at a daily time step, the routing component is not so critical. The PDM model has been implemented within a MATLAB toolbox with the option of calculating the actual evapotranspiration E_a as a function of the potential evaporation rate E_p, and the soil moisture deficit (Wagener et al., 2001):

$$E_a = \left\{1 - \left[\frac{(S_{max} - S(t))}{S_{max}}\right]\right\} \cdot E_p \tag{6}$$

where, S_{max} is the maximum storage and $S(t)$ is the actual storage at the beginning of the interval. A description of the model parameters is provided in Table 2.

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3.3 Comparison between the experimental water balance and the PDM model

The comparison between the experimental local water balance and the PDM model is carried out for the time period between July 2010 and November 2012, since that is the period for which the hydrological data are available for both catchments.

A split sample test is performed in order to assess the performance of the PDM model (Klemeš, 1986). The collected data contain wet and dry periods.

To implement the PDM model, an exploratory sensitivity analysis is done in order to define the feasible parameter range. The sampling strategy applied is a Latin Hypercube sampling with a genetic algorithm (Stocki, 2005). Afterwards, the parameters of the PDM model were optimized by means of the Shuffled Complex Evolution algorithm (Duan et al., 1992).

The reliability of the PDM model for this type of Andean catchments was assessed by means of the generalised likelihood uncertainty estimation (GLUE) methodology (Beven and Binley, 1992). A uniform prior parameter distribution and a Monte Carlo sampling technique are used to obtain 10 000 behavioural parameter sets. The Nash–Sutcliffe efficiency is the likelihood measure implemented in order to establish a threshold where it is expected that at least 90 % of the discharge observations are within the uncertainty bounds.

The PDM model estimates an average soil water storage for the entire catchment. This areal average can be compared with point measurements of the soil water content measured by TDR. The soil water storage data will be scaled in order to make the comparison by means of the Eq. (7).

$$S_r = \frac{S_o - S_{min}}{S_{max} - S_{min}} \tag{7}$$

where S_r = the time series of soil water storage scaled (0–1) [–], S_o = the time series of soil water storage with its original values [mm], S_{min} = the daily minimum soil water storage value [mm] and S_{max} = the daily maximum soil water storage values [mm].

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4 Results and discussion

4.1 The potential evapotranspiration derived from soil water observations

4.1.1 The potential evapotranspiration

The potential reference evapotranspiration (E_p) for the period from 16 July 2010 until 15 November 2012 was calculated by the FAO–Penman–Monteith approach with the solar radiation estimated by Hargreaves–Samani. The daily average of E_p for Calluancay and Cumbe was 2.35 and 3.04 mm day^{-1} respectively. The temporal variation of E_p is depicted in Fig. 2. It reveals a sinusoidal pattern with higher atmospheric evaporative demand during the drier months (from August to March) and a lesser demand during the subsequent wet periods (from April to July). E_p ranged between 0.76 and 4.17 mm day^{-1} for Calluancay and between 1.56 and 4.62 mm day^{-1} for Cumbe. The difference can be attributed to the altitude difference between both catchments, with 900 m difference in elevation. The daily average minimum and maximum temperatures in Calluancay were 3.0 and 10.2 °C respectively. While, in Cumbe they were 7.8 and 17.4 °C. In addition, the wind speed is different in both catchments. Calluancay is very exposed to prevailing winds while Cumbe is relatively sheltered. The daily average wind speed for Calluancay and Cumbe are 4.2 (max: 11.9) and 0.9 (max: 2.6) m s^{-1} respectively.

4.1.2 The vegetation coefficient

The time series during a wet period ranging between November 2007 and November 2008 (about a year) was used to estimate the vegetation coefficient, k_v for Calluancay. During this time period, the water content shows values greater or equal to field capacity (0.835 cm^3 cm^{-3}) (Table 1). So, this period is water stress-free and k_s was set to 1. For this wet period, k_v was estimated as 0.63. Similar but somewhat lower values in the range of 0.42 to 0.58 have been reported in the literature (Buytaert

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et al., 2006c). Variations in water use are sometimes explained by extensive livestock grazing, frequent burns of páramo and fertilization, which lead to a more vigorous and green vegetation with a larger k_v. Normally the páramo contains a lot of dead brown leaves with a low vegetation coefficient.

For Cumbe, the wet period observed between February and April 2012 was used to estimate k_v. The soil moisture values for that period are near to the field capacity ($0.531\,cm^3\,cm^{-3}$). Therefore, this wet period can equally be considered water stress-free. The vegetation coefficient was estimated to be 0.82. This value is consistent with the values established in the literature for grazing pastures (Allen et al., 1998), which are rather extensive and rough without high levels of fertilizer or cattle density.

Finally, the evapotranspiration derived from wet periods as identified by the soil water measurements in Calluancay and Cumbe was: 1.27 (range 0.53 to 2.35) and 2.51 (range 1.93 to 3.02) $mm\,day^{-1}$ respectively.

4.1.3 The water stress coefficient and the critical soil water content

The values of the k_v coefficient estimated during wet stress-free periods for both páramo vegetation (Calluancay) and for grazing pastures (Cumbe) are used during the drought period in 2010, to estimate the water stress coefficient and the critical soil water content. The latter are calculated by considering the soil water balance approach at the root zone during the pre-mentioned dry period. Based on the soil water observations, a suitable dry period was selected for each catchment. The water balance equation can be applied for Calluancay and Cumbe from July 2010 until February 2012. These periods show a negligible difference in root zone storage variation between start and end (Fig. 3).

Therefore, the water balance approach can be applied in both catchments. The critical water content in Calluancay was found to be $0.81\,cm^3\,cm^{-3}$. This value is very close to the field capacity, as determined in the laboratory (Fig. 3a). The Andosols have typically an extreme high water retention capacity (Buytaert et al., 2006a). The critical moisture in Cumbe was $0.50\,cm^3\,cm^{-3}$. This value is also near to the field capacity, as determined in the laboratory (Fig. 3b). Critical soil moisture values between ca. 50–80 % of field capacity are reported in the literature (Seneviratne et al., 2010). However, most of them correspond to mineral soils in the context of crop water requirements and therefore those values cannot be applied for the present study. High critical soil moisture could be partially explained by the plant physiology. It is important in páramo because the tussock grasses (mainly *Calamagrostis* spp. and *Stipa* spp.) are characterized by specific adaptations to extreme conditions. For instance, the plants have scleromorphic leaves which are essential to resist intense solar radiation (Ramsay and Oxley, 1997). In addition, the plants are surrounded by dead leaves that protect the plant and reduce the water uptake. As well as in Cumbe the grazing pastures are characterized by plants of type C3 (*Pennisetum clandestinum*) which are highly resistant to drought. Therefore, the water uptake is mainly regulated by the plants during dry periods. This is clearly observed in the TDR data (Fig. 3). The time series of soil water content reveal a constant rate of water uptake during dry periods.

4.2 The actual vegetation evapotranspiration derived from soil water observations

For Calluancay, the lowest value of k_s that was observed amounts to 0.62 (11 November 2010). For the same day, in Cumbe the k_s was 0.50. In other words, the water uptake by the roots was reduced by 38 % in the páramo and by 50 % for the pasture in Cumbe. This is a clear indication of the magnitude of the 2010 drought. A similar reduction could be expected for the drought event in 2009 as the soil moisture content was even a bit lower to the registered value in 2010 (Fig. 3a). Nevertheless, in these climate conditions the vegetation was affected significantly. In addition, the probability of human-caused fires in páramo is higher during dry periods. This could affect the resilience of the soils especially during the subsequent wet period, since the vegetation is the main factor influencing the infiltration of the water.

So, for the whole period, which includes the drought of 2010, the daily average of E_a, for Calluancay and Cumbe is 1.42 (range 0.48 to 2.37) and 2.09 (range 0.99 to 3.04) mm day^{-1} respectively.

The water balance in the two experimental catchments and its components expressed as cumulative volume over the period from July 2010 until February 2012 are given in Table 1 and Fig. 4. From this analysis it is clear that the páramo vegetation and soil are more resilient to drought as compared to the lower grass vegetation and soil. Especially the recovery after the drought period is much shorter. The lower potential evapotranspiration is an important reason. Both the reference crop evapotranspiration and the vegetation coefficient are lower, so that páramo consumes less water. According to our experimental results, during wet periods the proportion of the stream discharge that can be regarded as potential water use is 54 %. In addition the rainfall is slightly higher, so the runoff coefficient in páramo during the wet period remains at 0.68 of the rainfall and is still as high as 0.50 during the dry period. For the lower Cumbe catchment these coefficients are much lower: 0.21 and 0.23 for the wet and dry periods, respectively. Although the soil characteristics are very important for sustaining the base flow the different vegetation requirements are the crucial factors that explain these differences. Furthermore, the evaporative demand is higher in Cumbe as compared with Calluancay, due to the altitude difference. As a consequence, the length of recovery period for the drought event in 2010 was three months for the organic soils while in the mineral soils it took eight months (Fig. 3).

4.3 Actual catchment evapotranspiration estimated by hydrological modelling

An initial inspection of the discharge and rainfall data revealed that the drought period of 2010 was followed by a wet period induced by a flood event on 10 April 2011. On the other hand, 2012 was relatively normal with the classic bimodal pattern (wet and dry period) (Celleri et al., 2007).

Therefore, the time periods from 16 April 2011 until 16 January 2012 and from 17 January 2012 until 16 October 2012 are used as calibration and validation period respectively. These periods do not include the aforementioned extreme events. The selected periods for calibration and validation resemble the average climatic conditions of the southern Ecuadorian Andes (Buytaert et al., 2006b; Celleri et al., 2007).

The Table 3 and Fig. 5 depict the results of the implementation of the PDM model. The performance of the model for the calibration period is good (average Nash–Sutcliffe efficiency 0.74). But, during the evaluation period the bias is high and the number of samples inside of the uncertainty bound is only 64 % for both catchments. Important is that the point measurements of the soil moisture content are in line with the catchment's average soil moisture storage calculated by the conceptual model (Fig. 5).

The calibrated maximum storage capacity in Calluancay is two times higher as compared to the value for Cumbe (Table 2). This confirms the water holding capacity of the Andosols, despite the fact that the soils are shallow. The spatial variability of the topsoil moisture storage is also high in páramo, which is congruent with the field observations carried out during soil surveys. In Cumbe the spatial variability of the topsoil moisture storage is lower. The values of the parameter b for both catchments, that reflect the spatial variability of the storage capacity, also reflect this. The lower spatial variability is probably also the reason why the simulated and observed soil moisture storage agrees better in Cumbe (Fig. 5b). These results are in line with the literature (Brocca et al., 2012). The point measurements of soil moisture can thus be confirmed as representative for the catchment's average soil moisture storage or general wetness condition.

The daily average values of E_a, as estimated by the PDM models for Calluancay and Cumbe, are 1.34 (range 0.17 to 2.79) and 1.77 (range 0.34 to 3.50) mm day^{-1} respectively. The mean values are similar to those obtained by the water balance equation and soil moisture observations. However, the range of variation is different for both methods. More variation is observed in the time series of E_a estimated by the PDM model. This is more evident in the Cumbe catchment (see Fig. 6). The PDM model does not regard a critical soil moisture value and therefore there are no constraints on the evapotranspiration during dry periods. As a result, E_a is overestimated during these events.

5 Conclusions

The páramo ecosystem has a pivotal role in the hydrology and ecology for the highlands of the Andean region. The páramo is the main source of drinking water and irrigation and for hydropower projects. The hydrological capacity of the páramo is primarily attributed to its organic soils. Shallow organic soils with exceptional high retention and infiltration capacity regulate the surface and subsurface hydrology in this mountainous ecosystem. Nonetheless, in the recent past, human activities and climate change have induced a negative pressure on its ecological services. In addition, from 2005 the whole region has faced several drought events with an adverse ecological and economic impact. In this context, the present study is focused on the analysis of the resilience capacity of the páramo soils during drought events. Therefore, we analysed the hydrological response of the páramo soil during drought events observed in 2009, 2010, 2011 and 2012. The analysis was carried out based on the soil water balance in the root zone. Two experimental catchments from the highlands of the Paute river basin were selected and monitored during ca. 28 months. A typical catchment on the páramo at 3500 m a.s.l. was compared to a lower grassland one at 2600 m a.s.l.

Initially, the first aim was to estimate the actual evapotranspiration based on continuous time series of soil water content measurements. To this purpose, two parameters have been estimated, a vegetation coefficient k_v and the critical soil water content θ_{crit}.

The vegetation coefficient k_v is used to estimate the crop water requirement in the FAO–Penman–Monteith equation. k_v represents the proportion of water use by a vegetation as compared to the reference crop, under wet, stress free conditions. θ_{crit} is a threshold value from which the potential evapotranspiration is reduced linearly in function of the availability soil water content.

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The estimated coefficients k_v during the wet periods where the potential vegetation evapotranspiration is observed for both páramo's vegetation and grazing pastures were 0.63 and 0.82 respectively. These data are consistent with the literature. The k_v value is slightly higher than reported in previous studies in the case of páramo's vegetation, but obviously frequent burning and human intervention on this páramo generate more vigorous vegetation and so more demand for water. The critical soil water content for Andosols and Dystric Cambisols were 0.81 and 0.50 $cm^3 cm^{-3}$. The daily average actual evapotranspiration in páramo is low, 1.42 $mm\,day^{-1}$. While, for grazing pastures the E_a is 2.09 $mm\,day^{-1}$. From the water balance, the proportion of potential water use in the páramo of Calluancay is 54 %.

During the drought events in 2009 and 2010, the soil water content in páramo reached values never seen before. And so it was possible to establish the amount of water of the topsoil which is active during these dry periods. The reservoir can deliver a water volume equivalent to 0.24 $cm^3 cm^{-3}$ (this represents the maximum soil water content change) during extreme climate conditions such as the droughts in 2009 and 2010. In normal conditions the maximum change observed in the soil water content is no more than 0.05 $cm^3 cm^{-3}$. As consequence the real evapotranspiration can be reduced up to 38 % of its potential by stress conditions.

Thus, despite having suffered an extreme drought in 2009, the páramo soils recovered of another drought in 2010. During last period an extreme drought event was recorded in the entire Amazon River basin. In the páramo, three months of precipitations were enough to recover its normal moisture conditions. This did not occur at lower altitudes where mineral soils (Cumbe) needed about eight months in total to achieve this recovery. The combination of two factors explains the recovery of the páramo ecosystem, a big soil water storage capacity of Andosols and a low atmospheric evaporative demand due to altitude and the typical vegetation. These factors play a pivotal role in the resilience capacity to droughts especially in páramos with seasonal patterns as in Calluancay. Therefore, the páramo ecosystems have a high resilience to droughts.

In this context, point measurements of soil moisture in the topsoil (30 cm) were in line with the catchment's average soil moisture storage as estimated by the PDM model. The storage parameters of the PDM are also in line with field observations and literature. The E_a, is however overestimated by the PDM model as compared to the water balance based on soil water measurements.

Finally, the present research has shown the value of soil water measurements at representative sites as they correspond well to the soil storage as estimated in a conceptual model. A more realistic estimation of the actual evapotranspiration can be done on the basis of the soil water content measurements. As continuous soil water data logging by TDR requires large investments the locations have to be selected with great care so that this point measurements can be considered a reliable proxy for the catchment's average soil moisture storage.

The Supplement related to this article is available online at doi:10.5194/hessd-12-11449-2015-supplement.

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Table 1. The main characteristics and the water balance of the experimental catchments[a].

Name	Altitude (m)	Area (km^2)	Monitoring period	Type of period	Soil moisture[b] ($cm^3\,cm^{-3}$)	ETsim[c] ($mm\,year^{-1}$)	ET ($mm\,year^{-1}$)	Discharge ($mm\,year^{-1}$)	Rainfall ($mm\,year^{-1}$)	RC	Dominant land use
Calluancay	3589–3882	4.39	29 Nov 2007–12 Nov 2008[d]	WET	0.83–0.86	539	462	1000	1462	0.68	Páramo
			16 Jul 2010–1 Feb 2012[e]	DRY	0.62–0.86	431	529	525	1054	0.50	
Cumbe	2647–3467	44.0	2 Feb 2012–13 Apr 2012	WET	0.51–0.54	882	918	243	1161	0.21	Grazing pastures
			16 Jul 2010–1 Feb 2012	DRY	0.39–0.54	647	668	204	872	0.23	

[a] Climatic variables have been rescaled to yearly basis for comparison with literature. RC is the runoff coefficient.
[b] The average daily minimum and maximum soil moisture for each monitoring period.
[c] ETsim is the actual evapotranspiration estimated by the PDM model.
[d] Gaps in the soil moisture data (30 Nov 2007–18 Jan 2008, 14 Mar 2008–23 Mar 2008, 30 Apr 2008–19 May 2008, 26 Jun 2008–28 Jun 2008, 16 Oct 2008–20 Oct 2008).
[e] Gaps in the discharge time series of Calluancay (29 Oct 2010–23 Nov 2010, 13 Jan 2011–2 Feb 2011, 27 May 2011–28 Jun 2011). These gaps has been filled up using the PDM model.

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Table 2. The calibrated parameters of the PDM model.

Parameters	Description	Feasible range	Calluancay	Cumbe
c_{max}	Maximum storage capacity	30–120 [mm]	101.2	44.2
b	Degree of spatial variability of the storage capacity	0.1–2.0 [–]	1.82	0.21
f_{rt}	Fast routing store residence time	1–2 [days]	1.7	1.1
s_{rt}	Slow routing store residence time	10–50 [days]	14.3	32.5
$\%(q)$	Percentage flow through fast flow	0.25–0.75 [–]	0.58	0.42

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Table 3. The Nash and Sutcliffe efficiencies and the bias for the PDM models*.

Catchment	Total period		Period 1		Period 2		Split sample		
	NS (–)	Bias (%)	NS (–)	Bias (%)	NS (–)	Bias (%)	NS (–)	Bias (%)	AC (%)
Calluancay	0.73	−9.6	0.67	−10.0	0.83	−19.2	0.74	−20.9	65
Cumbe	0.81	−3.8	0.82	−3.0	0.78	−0.3	0.66	−17.5	64

* Total period: 16 Jul 2010–15 Nov 2012, Period 1: 16 Apr 2011–16 Jan 2012, Period 2: 17 Jan 2012–16 Oct 2012. The parameter set calibrated for period 1 is used for validation in the period 2 (split sample test). NS is the Nash–Sutcliffe efficiency and AC is the percentage of data (discharge) that falls inside the uncertainty bands.

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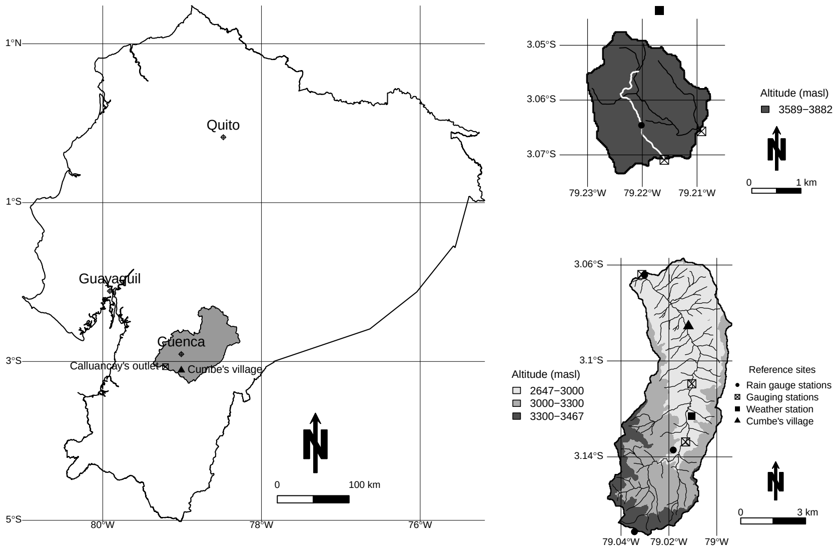

Figure 1. The study area.

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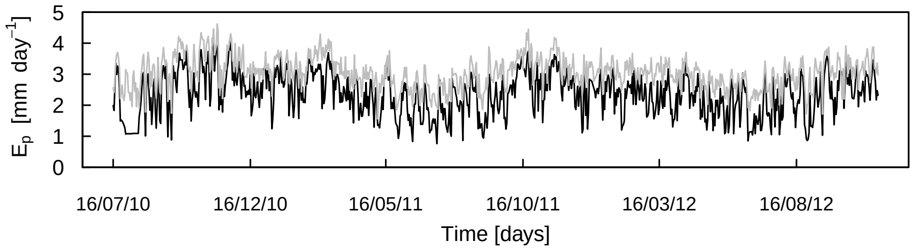

Figure 2. The potential evapotranspiration E_p for Calluancay (black) and Cumbe (grey).

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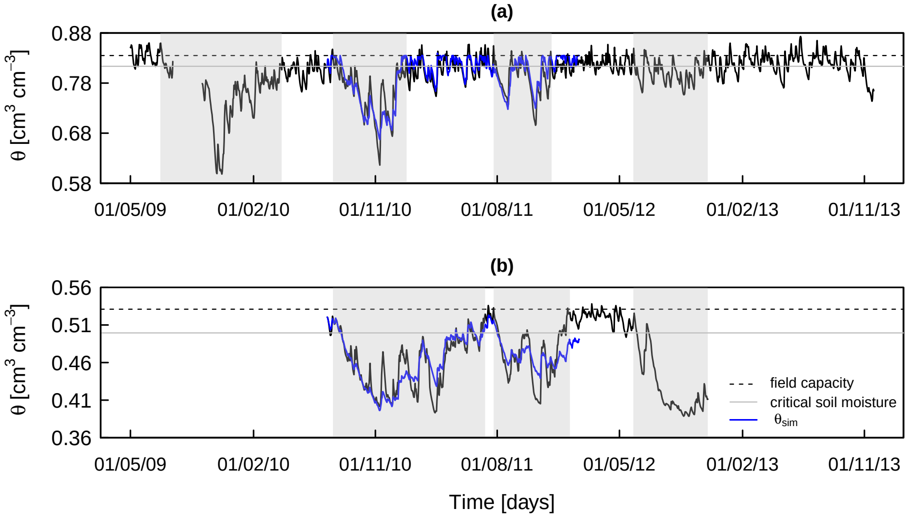

Figure 3. The soil water content data for Calluancay **(a)** and Cumbe **(b)**. The drought periods are shaded in grey. The blue lines show the soil water content simulated by means of the soil water balance in the root zone for each catchment during the period from on 16 July 2010 up to on 1 February 2012. In Supplement there are dotty plots with the parameters optimized during the water balance.

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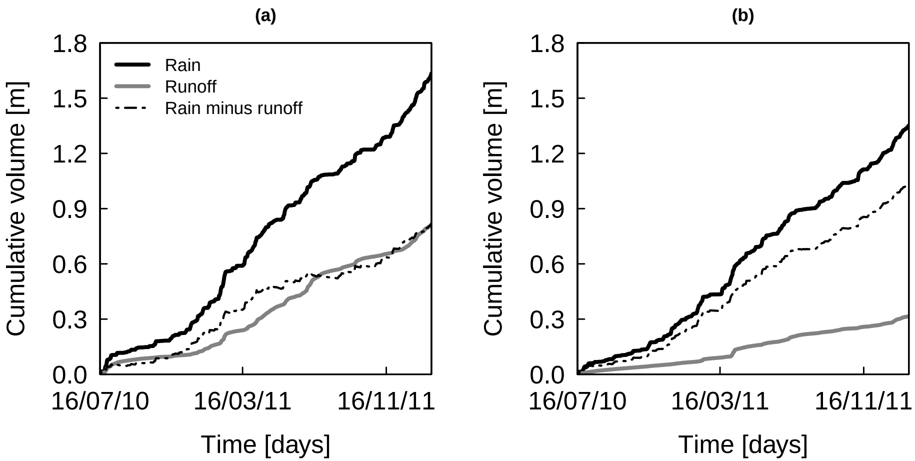

Figure 4. Water balance components for **(a)** Calluancay and **(b)** Cumbe. The curves in Calluancay show a non-linear behaviour and so suggest a seasonality for this páramo area. This climate pattern is enhanced by the occurrence of drought events. A high evapotranspiration is revealed in Cumbe. Most of this E_a can be attributed to the irrigation systems which are operational during dry periods.

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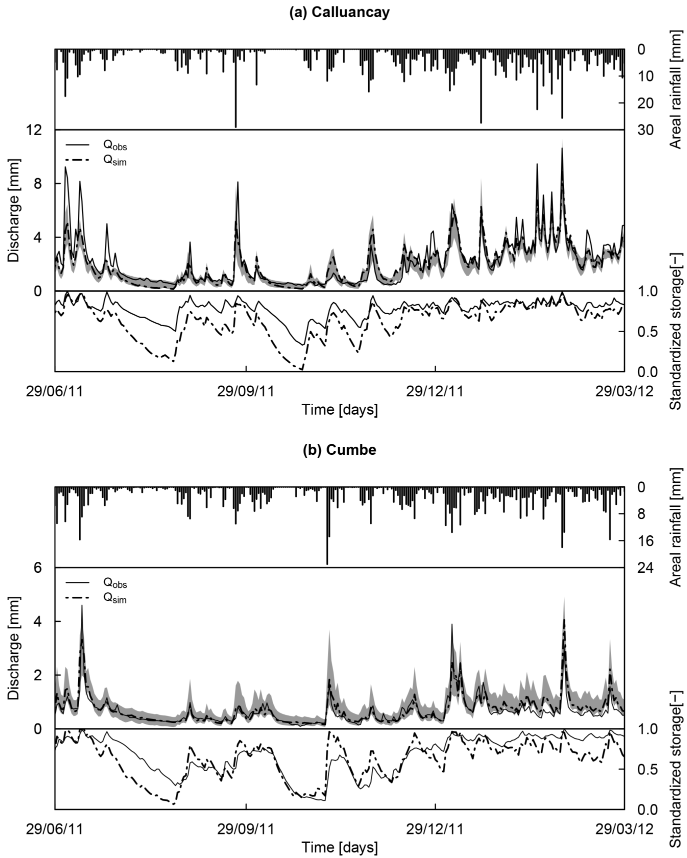

Figure 5. Representative sample of rainfall (top), runoff (middle) and soil moisture (bottom) time series. Uncertainty bounds are also included in the graphs. The scaled soil moisture storage in the root zone is shown in the bottom inset in the plot in solid and dashed black lines for measured and modelled respectively.

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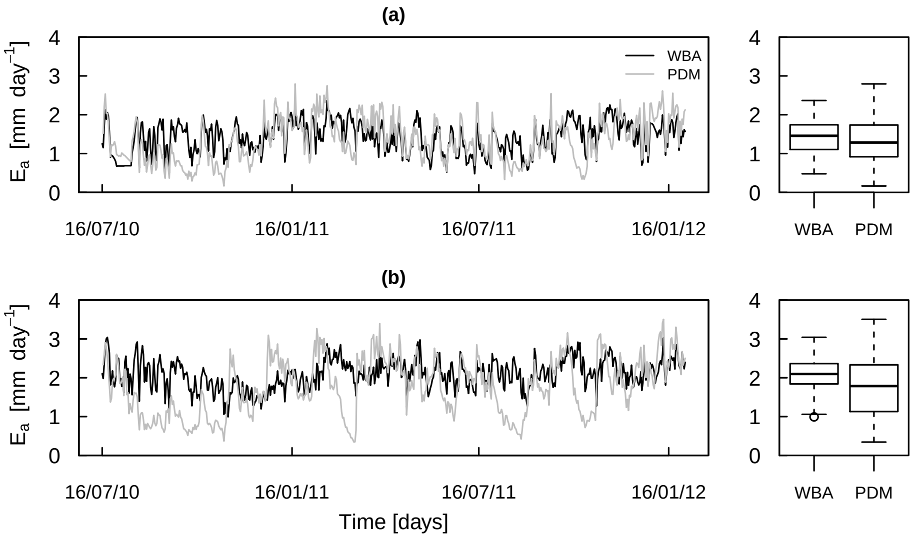

Figure 6. The actual evapotranspiration (E_a) using the water balance approach (WBA) and the PDM model. **(a)** Calluancay and **(b)** Cumbe.

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